High-Intensity Soil Mapping with the Aid of EMI in Northern Illinois

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abstract

While electromagnetic induction (EMI) has been used extensively in site-specific management, the use of this method in soil surveys has been limited. The appropriateness of using EMI to improve the quality of high-intensity soil surveys was explored at two sites in northern Illinois. At these sites, plots of apparent conductivity (EC_a) assisted field soil scientists in reevaluating soil mapping decisions, recognizing different soils, and modifying order-one soil maps. Independent core samples were extracted from each site to confirm impressions that the use of EMI improves the quality of these two surveys. At both sites, the core data showed slight improvements in the taxonomic purity of soil polygons when EC_a data were used. The most significant contribution of the EC_a data appears to be the increased confidence of soil scientists in their mapping decisions. As EC_a data can be rapidly collected and interpreted, the use of EMI, if available, is recommended for high-intensity or order-one soil surveys. However, the final soil map is decidedly more dependent on the expert knowledge of the soil scientist than on EC_a data alone.

The use of EMI methods to support high intensity soil surveys has not been adequately documented. Over the last decade, several studies have reported the synergistic use of global positioning systems (GPS), geographical information systems (GIS), aerial digital photography, terrain modeling, and mobile sensors to produce high-intensity maps for site-specific management (Corwin et al., 2008b; Adamchuk et al., 2004; Hedley et al., 2004; Corwin and Lesch, 2003; Godwin and Miller, 2003; Kravchenko et al., 2003; Fraisse et al., 2001; Jaynes et al., 1995). As a tool for site-specific management, EMI has been used to predict variations in crop yields, define management zones, direct soil sampling, and collect ancillary data, which can be associated with variations in soil properties (Jaynes, 1996).

Electromagnetic induction measures the apparent conductivity (EC_a) of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in EC_a are produced by changes in the electrical conductivity of earthen materials. Electrical conductivity is influenced by the type and concentration of ions in solution, the amount and type of clays, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). In general, the EC_a of soils will increase with increases in soluble salt, water, and/or clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

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Published in Soil Surv. Horiz. 50:68–74 (2009).

Because EC_a can be rapidly measured on a second-by-second basis from mobile platforms, data populations are relatively large, and sites can be more comprehensibly covered in shorter periods of time than with conventional survey tools and methods. Since large quantities of EC_a data can be recorded at relatively high levels of spatial resolution on a field-by-field basis, EMI surveys are considered high-intensity surveys. Because of the larger number of measurements, maps prepared from EC_a data often provide higher levels of resolution than those prepared with conventional tools or survey methods (Jaynes 1995). Jaynes (1996) reported that EC_a maps can be used as surrogates for soil maps. Spatial EC_a patterns identify areas with reasonably homogenous soils (Frogbrook and Oliver, 2007) and provide additional detail to existing soil maps (Hedley et al., 2004). A major contribution of EMI to soil surveys has been the identification and delineation of small included areas of dissimilar soils within soil polygons (Fenton and Lauterbach, 1999) and the general distribution of soils within fields (King et al., 2005).

Interpretations of EMI data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in EC_a have been used to infer changes in soils and soil properties (Corwin 2008; Wienhold and Doran, 2008; Kravchenko et al., 2002; Doolittle et al., 1996, 1994; Sudduth et al., 1995; Jaynes et al., 1993). Relationships between EC_a and soil properties vary at different spatial scales and can change over surprisingly short distances. The effectiveness of EMI as a soil mapping tool greatly depends on the degree to which differences in soil properties and changes in soil types correspond to measurable differences in EC_a. As different combinations of soil properties can simultaneously and to varying degrees influence EC_a across units of management, interpretations have been complicated and results inconsistent in many studies (Corwin et al., 2008a; Kern et al., 2008; Carroll and Oliver, 2005; Corwin and Lesch, 2003).

Soil maps prepared for most arable areas by the National Cooperative Soil Survey (NCSS) Program are considered second-order soil surveys. These maps are commonly prepared at scales ranging from 1:12,000 to 31,680 with minimum delineation sizes of 0.6 to 4.0 ha (1.5–10 ac), respectively (Soil Survey Staff, 1993). The adequacy and accuracy of standard soil surveys for site-specific management has been evaluated by Brevik et al. (2003) and Fenton and Lauterbach (1999). Compared with high-intensity surveys, second-order soil surveys have more variable soil polygons, and do not identify the locations of soil inclusions nor account for within-unit variability (Fenton and Lauterbach, 1999).

Compared with second-order soil surveys, which are prepared at smaller scales and typically on a county-by-county basis by the NCSS, high-intensity or first-order soil surveys are prepared for smaller parcels of land using different concepts, field procedures, kinds of map units, and minimum delineation sizes. First-order soil surveys contain more homogeneous map units, with the size and number of contrasting or dissimilar soil inclusions being more limited. High-intensity soil surveys entail the collection of more closely spaced information, and the imposition of more rigorous field standards and procedures. As a consequence of these standards and procedures, soil polygons contain less variability and are delineated at a higher level of resolution (Soil Survey Staff, 1993). Map units for high-intensity soil surveys are mostly consociations. Depending on the scale, the minimum delineation size is about 0.6 ha (1.4 ac) or smaller (Illinois Soil Survey Staff, 1999).

While EMI has been used extensively by the private sector for site-specific management, the use of this geophysical tool to prepare high-intensity soil maps has been very limited (Kitchen et al., 1998). First-order or high-intensity soil surveys are principally a private sector pursuit (Mausbach et al., 1993). However, the NCSS occasionally prepares first-order soil surveys at scales of 1:12,000 or larger to address special needs.

The use of EMI by field soil scientists within the USDA-NRCS has been limited. While the use of EMI within the NCSS has expanded in recent years, the integration of this geophysical tool into soil surveys is still being explored. Where EMI sensors are available, field soil scientists are uncertain as to their effective use in different soils and for different applications, the proper survey protocol, and the relevancy of EMI data in the preparation of soil maps. The use of EMI requires extra time and effort for the collection of EC_a data and the incorporation of this ancillary information into high-intensity soil maps, which are already burdened by more rigorous field procedures and standards. The use of EMI as an ancillary tool to support soil mapping decisions made by field soil scientists involved in the preparation of high intensity soil surveys has not been documented. Do the extra measures required for EMI surveys and data interpretations benefit field soil scientists and improve the accuracy of first-order soil surveys? In a previous study, spatial EC_a data were collected at a site in northern Illinois (Doolittle et al., 2008). This data did provide an additional layer of soil information, which was used to augment observations and interpretations made by field soil scientists tasked with producing high-intensity soil maps. At this site, the information provided by EC_a maps and additional soil sampling led soil scientists to recognize different soils, and alter some map unit names and boundaries. The purpose of the present study was to collect independent soil core data to confirm whether the use of EMI improved the quality of initial mapping and resulted in more homogenous soil consociations that contain lesser amounts of dissimilar soil inclusions at two high-intensity soil survey sites in Illinois.

Study Sites

The study sites are located in Warren and Stephenson Counties in northern Illinois. Both sites are about 32 ha (80 ac) and located in cultivated fields. The Warren County site is located in the E 1/2 of the SE 1/4 of Section 24, T. 8 N., R. 3 W. At this site, soils formed in relatively homogenous, deep loessial deposits. Soils that develop in deep loessial deposits are considered to have relatively homogenous properties, with major differences resulting from soil–landscape interactions (Vitharana et al., 2008). In the loess soils of Belgium, Vitharana et al. (2008) found that among soil and topographic properties, pH, EC_a, and elevation were the key properties for the delineation of potential management zones.

Soils at the Warren County site are Mollisols and Alfisols and belong to the fine-silty and fine particle-size and the superactive cation-exchange activity classes (Table 1). Although belonging to different particle-size classes, differences in clay contents among these soils are considered slight. Soils vary from very poorly drained to somewhat poorly drained Endoaquolls and Endoaqualfs and moderately well-drained Argiudolls. Typically, the poorly drained Sable (map unit symbol 68) and the very poorly drained Peotone (330) soils are on slightly lower-lying, more concave areas. Because both Peotone and Sable soils are wetter and subject to ponding, these soils are considered dissimilar and more limiting than the other soils recognized within this site. The somewhat poorly drained Ipava (43) and Muscatune (51), and the moderately well-drained Buckhart (705) soils are on slightly higher-lying and more sloping areas. Though taxonomically distinct, Buckhart, Ipava, and Muscatune soils are considered closely similar in use and interpretations. Small areas of Clarksdale (257) and Assumption (259) soils, although mapped in the northern portion of this site, were not included in the reported study.

The Stephenson County site is located in the W 1/2 of Section 7, T. 27 N., R. 8 E. Compared with the Warren County site, the loess mantle is noticeably thinner at the Stephenson County site. Contrasting layers of till, outwash, lacustrine sediments, and residual soil materials, as well as dolomite parent rock, were recognized in cores extracted from the Stephenson County site.

Because of the thinner loess mantle and the greater diversity of underlying materials, a larger number of soils were recognized at the Stephenson County site (Table 2) than at the Warren County site. Soils are Mollisols or Alfisols and belong to the superactive cation-exchange activity, and the fine, fine-silty, and fine-loamy particle-size classes. Within the study site, some soils were described with substrata of red residuum, till, paleosols, and/or dolomite bedrock. In addition, layers of

Table 1. Names, symbols, and taxonomic classifications of the soils recognized at the Warren County site.

Symbol	Soil series	Taxonomic classification
43	Ipava	Fine, smectitic, mesic Aquic Argiudolls
51	Muscatune	Fine-silty, mixed, superactive, mesic Aquic Argiudolls
68	Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
249	Edinburg	Fine, smectitic, mesic Vertic Argiaquolls
257	Clarksdale	Fine, smectitic, mesic Udollic Endoaqualfs
259	Assumption	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls
330	Peotone	Fine, smectitic, mesic Cumulic Vertic Endoaquolls
705	Buckhart	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls

Table 2. Names, symbols, and taxonomic classifications of the soils recognized or observed at the Stephenson County site.

Symbol	Soil series	Taxonomic classification
29	Dubuque	Fine-silty, mixed, superactive, mesic Typic Hapludalfs
40	Dodgeville	Fine-silty over clayey, mixed, superactive, mesic Typic Argiudolls
68	Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
69	Milford	Fine, mixed, superactive, mesic Typic Endoaquolls
86	Osco	Fine-silty, mixed, superactive, mesic Typic Argiudolls
152	Drummer	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
191	Knight	Fine-silty, mixed, superactive, mesic Argiaquic Argialbolls
199	Plano	Fine-silty, mixed, superactive, mesic Typic Argiudolls
219	Millbrook	Fine-silty, mixed, superactive, mesic Udollic Endoaqualfs
324	Ripon	Fine-silty, mixed, superactive, mesic Typic Argiudolls
344	Harvard	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
411	Ashdale	Fine-silty, mixed, superactive, mesic Typic Argiudolls
416	Durand	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
440	Jasper	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
448	Mona	Fine-loamy, mixed, superactive, mesic Oxyaquic Argiudolls
506	Hitt	Fine-loamy, mixed, superactive, mesic Typic Argiudolls
540	Frankville	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
663	Clare	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls
679	Blackberry	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls
731	Nasset	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
3107	Sawmill	Fine-silty, mixed, superactive, mesic Cumulic Endoaquolls

loamy outwash and silty/clayey lacustrine sediments were recognized. Though descriptively distinct, the perceived differences in many of these parent materials were often subtle and difficult to distinguish in the field.

Material and Methods

Two geophysical tools were used in this study: the Veris 3100 soil EC mapping system (hereafter referred to as the Veris system), and the EM38 meter.[1] The Veris system is a towed-array, multi-electrode resistivity unit manufactured by Veris Technologies (Salina, KS). Operating procedures are described by Veris Technologies (1998). The Veris system provides two soil measurement depths: one for the upper 30 cm (12 in, shallow) and one for the upper 90 cm (35 in, deep). The Veris system was pulled behind a 4WD vehicle at speeds of about 4.8 to 9.7 km/h (3–6 mi/h). A Trimble 132 GPS receiver (Sunnyvale, CA) was used with the Veris system to georeference the collected EC_a data.

The EM38 meter is manufactured by Geonics Limited (Mississauga, Ontario). This meter is portable and needs only one person to operate. The EM38 meter has a 1-m (39-in) intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, the EM38 meter provides theoretical penetration depths of about 150 cm (59 in) in the vertical dipole orientation. Operating procedures for the EM38 meter are described by Geonics Limited (1998). The EM38 meter was towed in a plastic sled behind an all-terrain vehicle at speeds of 1.6 to 3.2 km/h (1–2 mi/h). A Garmin Map 76 GPS receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack) (Olathe, KS), was used with the EM38 meter to record location data. An Allegro CE field computer (Juniper Systems, North Logan, UT) was used to record and store both EC_a and GPS data.

At each site, soil descriptions were collected from cores extracted with truck-mounted Giddings soil probes (Giddings Machine Company, Windsor, CO).

All soil data were scanned and digitized using Arc/Info and imported into Arc View 3.3. Using Arc View 3.3, soil polygons were overlain (at a display scale of 1:7,920) on recent aerial photographs of each site. Layers of EC_a data were subsequently overlain onto these images.

[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

At each site, two order-one soil surveys had been completed in accordance with Illinois standards and procedures (Illinois Soil Survey Staff, 1999). At both sites, the first order-one soil survey was completed without the aid of EC_a data. Before the second order-one soil surveys, detailed EC_a data were collected at each site. The second order-one soil survey of each site was completed by the same soil scientists using tacit knowledge gained from the first survey plus ancillary EC_a data. The information provided by EC_a maps and additional soil sampling led these soil scientists to reevaluate soil mapping decisions and conceptual soil landscape models, recognize different soils, and modify soil maps. Within the two study sites, plots of EC_a data assisted soil scientists to identify and delineate some soil polygons. Overall, soil scientists sensed, but could not confirm that the availability of EC_a data helped to improve the quality of the two high-intensity soil maps. Results from the high-intensity soil surveys at the Stephenson County site and the impressions of the involved soil scientists have been reported by Doolittle et al. (2008).

In the fall of 2006, to substantiate the impressions of the soil scientists involved in the mapping, and to verify the relative accuracy of the two order-one soil surveys, soils were observed by an independent group of soil scientists using a relatively coarse (100-m or 328-ft interval) grid sampling scheme. This scheme provided a total of 50 observation points at each site. At each observation point, soil cores were observed and described to a depth of 2.0 m (79 in) or to bedrock. Brief profile descriptions were prepared and soils were taxonomically identified (Soil Survey Staff, 2006) using standard field procedures (Soil Survey Staff, 1993) at each observation point. The location of each observation point was recorded with GPS. For each site, the coordinates of these soil observation points were overlaid onto the two order-one soil maps for interpretation and analysis. Observation points that fell on soil polygon lines were included in the polygon that most closely identified the observed soil. At some observation points, soils were identified as intergrades between soil series. For the purpose of this investigation, intergrades were considered to be the series that they most closely resembled.

Results and Discussion

Warren County Site

Figure 1 shows images of the two order-one soil surveys that were completed at Warren County site. The left-hand plot shows the first order-one soil map, which was completed in 2005. The right-hand plot shows the second order-one soil survey, which was completed in 2006. In each image, soil boundary lines and map unit symbols (see Table 1) are shown. Also shown in each plot are the locations and identities of the soils that were observed at the fifty soil core sites. As evident in these images, the second soil survey resulted in changes to some map unit names and readjustments of some polygon boundaries. Kitchen et al. (1998), comparing three different first-order surveys of the same 35.6 ha (88 ac) field in central Missouri, noted the difficulty of obtaining repeatable results using traditional soil survey methods. Because of their subjectivity, soil boundaries drawn by soil scientists often lack repeatability (Fraisse et al., 2001). In areas that lack abrupt and contrasting changes in soil properties and clear external expression of changes in soils, it is difficult to accurately and precisely locate boundary lines between soil polygons (Hudson, 1992).

Figure 2 contains plots of EC_a data from the Warren County site, which were measured with the Veris system in the shallow (left-hand plot) and deep (right-hand plot) configuration. In both plots, the isoline

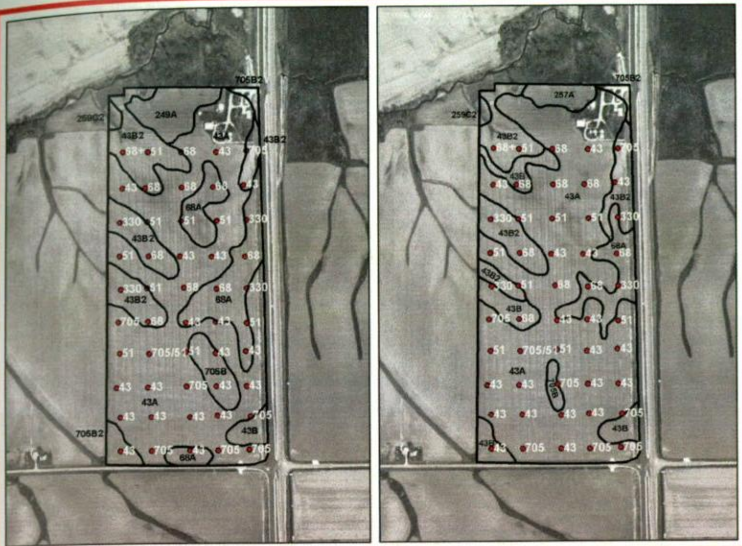


Fig. 1. These images show soil polygons that were mapped in the first (left-hand) and second (right-hand) order-one soil surveys of the Warren County site. Also shown are the locations and identities (corresponds to consociation symbol) of the soils observed at the soil coring sites.

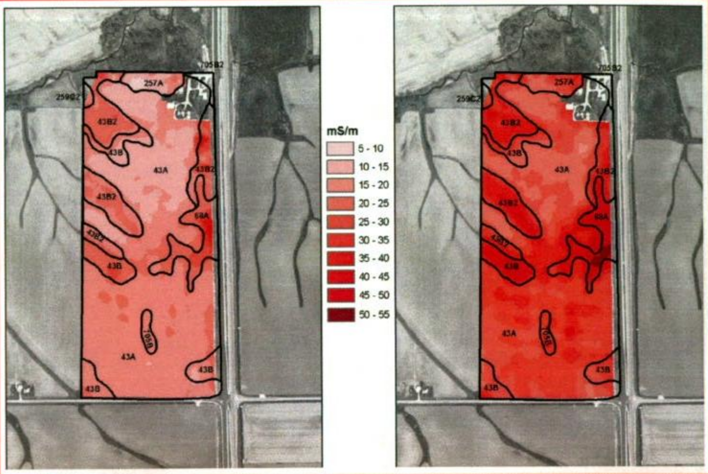


Fig. 2. Spatial patterns of EC$_a$ data obtained with the Veris system are overlain onto plots of the second order-one soil survey of the Warren County site. Measurements were obtained with the Veris System in the shallow (left) and deep (right) configurations.

interval is 5 mS/m, and the same color scale is used. Also shown in these plots are the soil polygons and map unit symbols from the second order-one soil survey map. Within this site, variations in EC$_a$ are principally attributed to differences in soil moisture. In general, areas of higher EC$_a$ are associated with wetter areas of Sable and Peotone soils along drainageways. Areas with lower EC$_a$ are associated with better drained, higher-lying areas of Ipava, Muscatune, and Buckhart soils.

The availability of EC$_a$ data did influence mapping decisions of the soil scientists. Based on relative EC$_a$ values and spatial patterns, two polygon of Sable (68A) soils, which had been mapped on slightly higher-lying areas during the first high-intensity survey, were reevaluated and removed in the second order-one soil survey (see Fig. 1). Soils in these areas were recognized as being more similar to the central concepts of the Ipava (43A) than Sable (68A) soils. In these areas, EC$_a$ values were lower and the soils were considered better drained than the more representative and lower-lying area of Sable soils along the eastern boundary of the site. More sloping and eroded areas of Ipava (43B2) soils were also reevaluated. Portions of these polygons, which displayed slightly lower EC$_a$ and thicker surface layers, were remapped as Ipava (43B) soils. The more sloping areas of these polygons (43B2) have thinner surface layers and usually displayed higher EC$_a$, which was attributed to the distribution of clays and seepage. Because of landform position and slightly higher soil moisture, areas of Edinburg (249A) soils with higher EC$_a$ were remapped as Clarksdale (257A) soils. Areas of Edinburg (249A) soils with lower EC$_a$ were remapped as Ipava (43A) soils. In addition, along the eastern border of the site (see Fig. 2), polygon boundaries of Ipava (43B2) and Sable (68A) soils were adjusted to more closely approximate spatial EC$_a$ patterns.

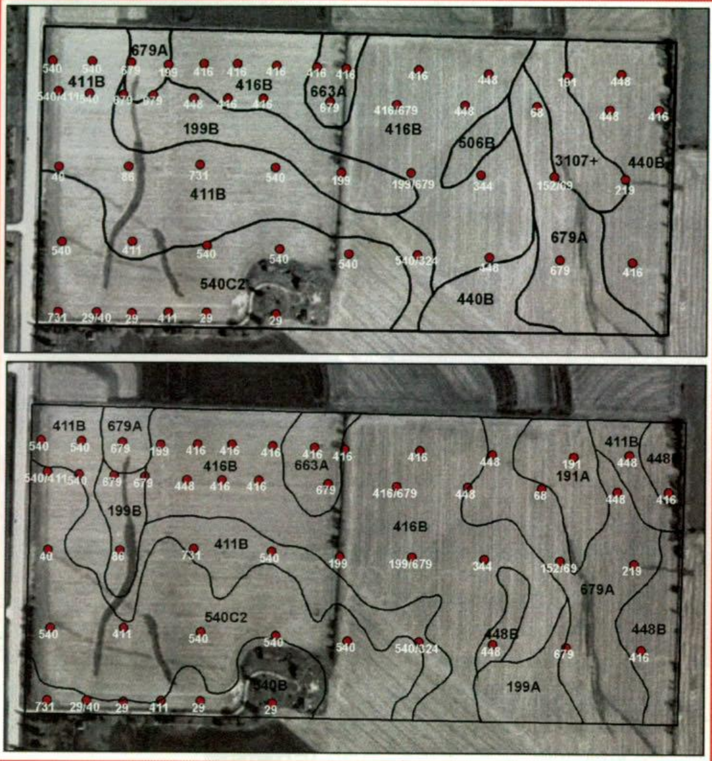
Table 3 provides basic statistics for the EC$_a$ data collected with the Veris system at the 50 core sites. The data are grouped according to the soil identified at each core site. The average EC$_a$ is higher in areas of Sable and Peotone soils. These soils are Aquolls and have higher soil moisture contents. The average EC$_a$ is lower in areas of Ipava, Muscatune, and Buckhart soils. These soils occur on higher-lying, better drained landscape components and are Argiudolls.

The data shown in Table 3 suggest that differences in EC$_a$ exist among the soils. An analysis of variance was used to test for significant differences in EC$_a$ among the five recognized soils. The null hypothesis was that the average EC$_a$ for all soils is the same. For shallow measurements collected with Veris System, EC$_a$ was not significantly different among these five soils. However, for the deep measurements, the average EC$_a$ was considered significantly different (F value = 3.78; P = 0.009) for the five soils. Although the sample population was small, results suggest that sufficient differences in EC$_a$ measurements (for the upper 90-cm [35.4-in] depth interval) exist among and may be helpful to identify and delineate these soils.

At the Warren County site, most soils cores were extracted from Ipava (43A, 43B, 43B2) and Sable (68A) polygons. For both soil surveys, the taxonomic composition of these map units were evaluated based on the soils identified at the core sites. For the first order-one soil survey, named or similar soil components comprised 42 to 100% and averaged 72% of the soils observed in cores extracted from these four soil map units. For the second soil survey, named or similar soil components comprised 50 to 100% and averaged 84% of the soils observed in cores extracted from these four map units. Compared with the first order-one soil survey, the second order-one soil survey, which was influenced by the EC$_a$ data, resulted in an increase in the proportion of named or similar soils, and more taxonomically homogenous map units.

Table 3. Basic statistics for the EMI survey of the Warren County site that was conducted with the Veris 3100 Soil EC$_a$ Mapping System.

Soil series	Number of observations	Veris Deep			Veris Shallow		
		Mean	SD	SE	Mean	SD	SE
Ipava	19	31.42	4.30	1.40	17.37	1.80	0.77
Muscatune	9	29.67	5.59	2.04	16.67	3.12	1.12
Sable	10	36.00	10.21	1.94	20.00	5.98	1.07
Peotone	4	42.00	5.42	3.06	22.50	2.63	1.19
Buckhart	8	32.12	3.36	2.17	18.38	2.13	1.19



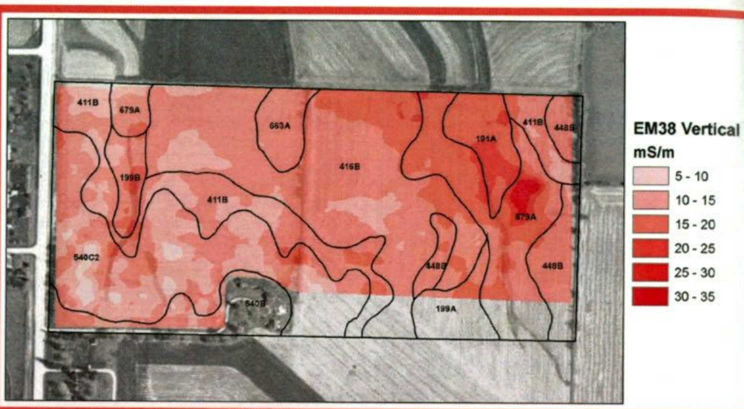


Fig. 3. (Left) These images show soil polygons that were mapped in the first (upper plot) and second (lower plot) order-one soil surveys of the Stephenson County site. Also shown are the locations and identities (corresponds to consociation symbol) of the soils observed at the soil coring sites.

Fig. 4. (Above) Plot of EC_a data were obtained with the EM38 meter, operated in the vertical dipole orientation, is overlain with the second order-one soil map of the Stephenson County site.

For both soil surveys, more limiting, poorly drained Sable (68) and very poorly drained Peotone (330) soils were observed in cores extracted from the somewhat poorly drained Ipava (43A, 43B, and 43B2) polygons. For the first soil survey, the more limiting Sable and Peotone soils comprised 0 to 58% and averaged 28% of the soils observed in cores extracted from these Ipava map units. For the second soil survey, Sable and Peotone soils comprised 0 to 50% and averaged 16% of the soils observed in cores extracted from these Ipava map units. Compared with the first order-one soil survey, the second order-one soil survey, which was influenced by the availability of EC_a data, resulted in a reduction of dissimilar and more limiting inclusions in polygons mapped as Ipava soils.

For both surveys, areas of Ipava (43), Muscatune (51), and Buckhart (705) soils were treated as dissimilar, nonlimiting inclusions in areas of Sable (68) soils. Based on the locations of the extracted cores on the first soil map, these dissimilar, nonlimiting soils comprised 50% of the soils observed in the Sable polygons. Based on the second soil map, these dissimilar, nonlimiting inclusions were not identified in the cores extracted from Sable polygons.

On the basis of the independent cores extracted from the Warren County site, the use of EC_a data resulted in an increase in the proportion of named or similar soils, a reduction in the proportion of dissimilar inclusions, and more homogenous consociations.

Stephenson County Site

Compared with the Warren County site, the Stephenson County site contains a larger number of soils with more variable properties. At the Stephenson County site, soils formed in a thinner loess mantle and in different and more variable parent materials. Within this site, soils varied from poorly drained Albolls and Aquolls to well-drained Argiudolls and Hapludalfs. Depending on location within the site, variations in EC_a were associated with differences in either moisture content or depth to more electrically resistive dolomite parent rock.

Figure 3 shows images of the two order-one soil surveys that were completed at this site. The upper image shows the first soil survey, which was completed in 2001. The lower image shows the second soil survey, which was completed in 2004. Also shown in each image are the locations and identifying soil symbols for the 50 soil cores extracted from this site in 2006.

Compared with the first survey, the second order-one soil survey resulted in the recognition of fewer soils (8 vs. 9), but a greater number of map units (10 vs. 9) and soil polygons (14 vs. 11) (Doolittle et al., 2008). Differences in the two maps are attributed to the variability of soils within the study site, availability of soil information from the previous survey and EC_a data, and refinements in the judgments of the soil scientists.

Figure 4 is a plot of the EC_a data measured in 2006 with an EM38 meter operated in the vertical dipole orientations at the Stephenson County site. The isoline interval is 5 mS/m. Soil polygons and map unit symbols are from the second order-one soil survey map. Some EC_a patterns approximate the general distribution of soils across the landscape, with lower-lying or wetter polygons of Knight (191) and Blackberry (679A) soils having higher EC_a than higher-lying, more sloping, better drained and/or shallower-to-bedrock polygons of Frankville (540) and Ashdale (411) soils. While some similarities between soil and EC_a patterns do exist, disparities are apparent in this image. Most soil polygon boundary lines and EC_a patterns appear to be either offset or to cross one another and define slightly different areas. The placement of many of the soil boundary lines more closely conformed to breaks in landscape components and slopes that were observed and used by the soil scientists during the completion of the soil survey. While the EC_a patterns influenced the judgments of soil scientists, EC_a maps were not accepted as a substitute for other factors used to make the soil map.

Relationships between EC_a and soil properties are often complex and variable within units of management. Carroll and Oliver (2005) noted that the strength of relationships between different soil properties and EC_a often varies in different portions of the same field or across units of management. At the Stephenson County site, soil depth (or depth to bedrock) and moisture content (or soil drainage class) were strongly associated with EC_a, but the strength of these associations varied across the site and with landscape position. On higher-lying areas, EC_a was principally associated with the depth to bedrock; on lower-lying areas, where the depths to bedrock are greater than 2 m (79 in, deeper than the nominal penetration depth of the EM38 meter), EC_a was principally associated with differences in soil drainage class.

In the second order-one soil survey of the Stephenson County site, some polygon boundaries were adjusted and names changed based on the influence of EC_a values and spatial patterns on the judgments of the soil scientists (see Fig. 3). In the eastern portion of the site, based on EC_a measurements and spatial patterns, portions of a Jasper (440B) polygon were remapped as areas of Mona (448B) soils. Here, relatively higher EC_a was associated with slightly higher moisture contents, which are more characteristic of the Mona (Oxyaquic Argiudolls) than Jasper (Typic Argiudolls) series. Also, in the eastern portion of the site, the boundary of a polygon of Blackberry (679A) soils was expanded to include a larger proportion of the area on either side of a drainageway, which displayed higher EC_a. In the southwest portion of the site, a polygon of Frankville (540C2) soils was expanded. This decision was based principally on spatial patterns of lower EC_a, which were associated with shallower depths to dolomite. Higher EC_a along a slight drainageway led to the recognition of this minor landform and a polygon of Plano (199B) soils in the western part of the site.

Within the Stephenson County site, the observed inverse relationship between EC_a and elevation partially reflects variations in soil moisture contents with landscape position. However, based on field observations, within higher-lying areas, the thickness of the soil column and/or depth to bedrock appears to have a greater affect on EC_a than soil moisture. In a previous study at this site (Doolittle et al., 2008), a moderate correlation (r) of 0.666 (significant at 0.02 level) was obtained between EC_a and bedrock depth measurements. On upland areas located in the southwest portion of this site, EC_a is generally higher where the soil column is thicker over the more electrically resistive dolomite bedrock.

Basic statistics for the EC_a data collected at 36 of the 50 core sites are listed in Table 4. The EC_a data were grouped according to the soils identified at the core sites. Only five soils were observed in four or more cores. These soils are listed in Table 4. The average EC_a was slightly higher in areas of Durand, Mona, and Blackberry soils. These very-deep, medium-textured, well-drained and moderately well-drained soils are Argiudolls. The average EC_a was lower in areas of Dubuque and Frankville soils. These moderately deep (over dolomite bedrock), well-drained, medium-textured soils are Hapludalfs.

Table 4. Basic Statistics for the EMI survey of the Stephenson County site that were conducted with the EM38 Meter in the Vertical Dipole Orientation.

Soil Series	Number of observations	Mean	SD	SE
Dubuque	4	13.50	1.73	1.14
Durand	11	17.23	1.75	0.69
Mona	6	18.50	3.51	0.93
Frankville	10	15.40	2.17	0.72
Blackberry	5	17.40	2.07	1.02

An analysis of variance was used to test for significant differences in EC_a among the five most commonly observed soils in the extracted cores at the Stephenson County site. The null hypothesis was that the average EC_a for all of these soils is the same. The mean sample EC_a for the thirty-six core sites was 16.5 mS/m. The standard deviation was 2.6 mS/m. The average EC_a was considered significantly different (F value = 3.948; $P = 0.01$) among the five soils. These results suggest that differences in EC_a may be used as a potential predictor of some soils within the Stephenson County site.

The EC_a measurements from the five soils were next grouped by depth to bedrock and drainage class. The moderately deep, well-drained Dubuque and Frankville soils are considered similar (both Hapludalfs) and were grouped together. The very deep, well-drained and moderately well-drained Durand, Mona, and Blackberry soils are considered similar (all Argiudolls) and were grouped together. An analysis of variance was used to test for significant differences in EC_a among the soil cores that were extracted in these two soil groupings. The null hypothesis was that the average EC_a for both groups of soils is the same. For measurements collected with the EM38 meter in the vertical dipole orientation, the average EC_a was significantly different (F value = 12.439; $P = 0.001$) for the two groups of soils. Within the Stephenson County site, soils appear to be more distinguishable based on general groupings that consider taxonomic classification, soil depth, and soil drainage class.

At the Stephenson County site, for both soil surveys, map unit compositions were evaluated based on the taxonomic identity of the soils at the core sites. Fifteen different soils were recognized at the 50 core sites. Based on the first order-one soil map, named or similar soil components comprised 30 to 100% of the soils observed in cores from the eight sampled soil consociations (see Fig. 3). Based on the second order-one soil map, the named or similar soil components comprised 33 to 100% of the soils observed in cores from nine sampled soil consociations. Compared with the first soil survey, the second soil survey has, on average, a slightly higher percentage (82 vs. 78%) of named or similar soils recognized in the names of the consociations at the core sites. However, for both surveys, in most polygons, the named soil makes up less than 50% of the soils observed in the cores.

For both surveys, poorly drained and more limiting Sable (68), Drummer (152), Knight (191), and Sawmill (3107) soils and moderately deep to bedrock Dubuque (29), Dodgeville (40), Ripon (324), and Frankville (540) soils were observed in cores extracted in areas of very deep, well-drained and moderately well-drained soils. Though sampling was limited, based on the first soil map, dissimilar and more limiting soils comprised 0 to 70% and averaged 22% of the soils observed in the extracted cores. Based on the second soil map, dissimilar and more limiting soils comprised 0 to 67% and averaged 18% of the soils observed in the extracted cores. Based on limited core data, the resurvey using EC_a data resulted in a slight reduction in the amount of dissimilar soils in soil polygons.

The second order-one soil survey of the Stephenson County site produced a greater number of soil polygons, but recognized more soils. However, soil cores provided no evidence that the second soil survey greatly improved the accuracy of the soil maps. The Stephenson County site is admittedly more variable than the Warren County site with a larger number of soils that were formed in more diverse parent materials. At the Stephenson County site, while most soils could not be clearly identified on the basis of EC_a alone, the use of EMI appears more effective in discriminating major soil types when the landscape is partitioned into groupings based on taxonomic classifications, soil depth, and drainage classes. This partitioning of the landscape is in agreement with the observation that spatial EC_a patterns are more likely to conform to the general, but not specific soil polygon patterns mapped by soil scientists.

Summary and Conclusions

This study was conducted by field soil scientists who have been involved in the production of order-one soil survey maps in Illinois. The purpose of this investigation was to evaluate the relevancy of EMI to improve soil map unit taxonomic purity in two diverse settings in northern Illinois. Within the two selected study sites, EC_a maps assisted soil scientists to identify and delineate some soil polygons and to help improve the quality of high-intensity soil surveys. At both sites, independent core data showed slight improvements in the taxonomic purity of order-one soil map units when EC_a data were used. The most significant contribution of the EC_a data appears to be the increased confidence of soil scientists in their mapping decisions. The information provided by EC_a maps and additional soil sampling led soil scientists to reevaluate soil mapping decisions and conceptual soil landscape models, recognize different soils, and modify soil maps. Since EC_a data can be rapidly collected and interpreted, the use of EMI, if available, is recommended for high intensity or order-one soil surveys. However, the final soil map is decidedly more dependent on the expert knowledge of soil scientists than on EC_a data alone.

Acknowledgments

We wish to acknowledge the contributions of the following Illinois soil scientists, without which, this paper would not be possible: Brad Boggus, Ron Collman, Steve Elmer, Erik Gerhard, Gary Hankins, Frank Heisner, Steve Higgins, and Steve Zwicker.

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